**Final Report on ONR Contract N00014-87-K-0505**

(1) Contract Title: Sources of Cloud Nuclei and Development of Remote Sensing Techniques for Cloud Parameters

1989

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ONR Program Managers: Dr. P. F. Twitchell/Dr. W. A. Hoppel

(2) Technical Objectives: Development of remote sensing methods for determining cloud and fog parameters, using passive techniques. Development and improvement of mathematical inversion procedures for remote sensing. Field and laboratory measurements of cloud nuclei.

(3) Approaches: Theoretical modelling (by radiative transfer theory) of cloud layers and discrete clouds under solar illumination in the visible and near-infrared; identification therefrom of spectral features and/or differences which would enable differentiation (without direct insitu sampling) of (for example) ice clouds from water clouds, large drops from small drops, etc. Development and field utilization on a modest scale of experimental systems to verify (or disprove) these concepts suggested by the theoretical modelling. Development of relevant numerical techniques for forward and inverse problems.

Application of CCD cameras, laser illumination and video/digital technique for droplet counting in thermal diffusion cloud chambers.

(4) Technical Accomplishments:

(a) Cloud reflectance spectra in the 1-2.5 μm region: During the contract period, two versions of a telespectrometer for the near-infrared were constructed. (The second version extended the spectral range and improved signal/noise and data logging rates. Both versions employed digital signal averaging). During several summers extensive data was collected from growing clouds during the monsoon season. Repeatedly a distinctive and abrupt change in the reflected spectrum was observed which numerical calculations showed to signal uniquely a transition from liquid to solid (ice). The experimental system was installed at a DRI field site in Truckee, California in late 1986 in conjunction with a Bureau of Reclamation-funded field project (SCPP-Sierra Cooperative Pilot Project). Even though the configuration (upward-looking) and the intensity levels (radiation transmitted down through the overlying cloud layer) were different from those for which the equipment was originally designed, excellent transmission spectra were obtained. Many of these enabled identification of the cloud as (predominantly) liquid, solid (ice) or mixed-phase. Subsequent theoretical computations gave spectra which agreed well with the measured spectra under the Sierra winter clouds, and in-situ measurements, when they were available from participating cloud physics aircraft, confirmed the remote sensing results.

Significance: We now consider that we have adequately demonstrated at the basic research level, the value of near-infrared spectra, whether reflected from or transmitted through the cloud, as a means of differentiating liquid water from ice. The presence of supercooled liquid water is essential for successful cloud seeding; it is also responsible for aircraft and helicopter icing. Our work therefore has potential application in both those areas, as well as for basic meteorology and cloud physics. Several papers have been published on the technique (see Publication List, below).

(b) Satellite applications: Present satellites do not carry anything similar to the near-infrared spectrometer described above. We therefore studied existing civilian satellite sensors and wavelengths. The study suggested, and computations confirmed, that Landsat Thematic Mapper channels 5 and 7 should be applicable for discriminating liquid water from ice, if the ratio of reflectance (cloud brightness) for those two channels was used as discriminator--for ice this ratio is around 1.2, and only slightly size-dependent, but for water it is larger--from ~1.25 to 2.0

depending on drop size. Initially we chose radiometric data for a cloud scene which could not include any ice (cloud top temperatures were above freezing), in order to test the algorithm first in a known situation. The ratios fell clearly in the "liquid" category, being clustered mainly in the range 1.6-2.0.

(c) Tomography/inversion methods: Iterative methods previously developed were extended to a much larger problem--an atmospheric 2-dimensional temperature field involving 5000 unknowns and 3600 hypothetical measurements (using transmission data for NOAA VTPR satellite's infrared and microwave channels). The algorithm has proved to be quite stable, and returned 80% of the unknowns to within 2°K of the correct value. We are currently studying performance in more detail and propose to compare a simulated retrieval by more conventional methods from the same data.

(d) CCD-based cloud nucleus measurement techniques: In late 1988, Prof. Charlson (University of Washington) invited us to participate in a marine DMS-related research cruise, our role to be measurement of cloud nuclei. Dr. Twitchell encouraged this idea, and equipment was put together and tested. It operated on a continuous basis during the NOAA McArthur cruise (June 1989), providing a monitoring measurement every ten minutes at 0.75% supersaturation and a spectrum over the range 0-2% once every hour. About 20 spectra and almost 1500 single-supersaturation monitoring measurements were obtained. The instrument package will be used in a similar project in 1990.

Significance: The role of cloud nuclei has received a lot of attention in the last couple of years in the context of climate change, but actual measurements have been few. Our participation in the NOAA research cruise provided a set of data for nucleus concentrations and spectra for inclusion with numerous air- and ocean-chemistry measurements of DMS and other potentially important trace constituents. For the Navy, a lightweight automated instrument for cloud nucleus measurements would be needed, for example for a survey by aircraft of nucleus concentrations in the lee of ships. Nuclei emission in sufficient number can change the reflected brightness of an overlying cloud and to a platform above the cloud reveal the presence of the vessel and its course and speed.

(5) Personnel

S. Twomey (P.I.)

S. G. Bradley

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(6) Publications:

P. Pilewskie, 1989: Cloud phase discrimination by near-infrared remote sensing. Univ. of Arizona, PhD Dissertation.

S. Twomey, 1989: Comments on "Delayed albedo effects in a zero-dimensional climate model", J. Geophys. Res., 94, No. D11, pp. 13,145-13,149.

S. Twomey and T. C. Cocks, 1989: Remote sensing of cloud parameters from spectral reflectance in the near-infrared, Contributions to Atmospheric Physics, 62, pp. 172-179.